MUR-8577US

PATENT SPECIFICATION

(11) 1 552 864

1 552 864

(21) Application No. 1113/79 (22) Filed 12 May 1976

(62) Divided out of No. 1552863

(31) Convention Application No. 576623 (32) Filed 12 May 1975 in

(33) United States of America (US)

(44) Complete Specification Published 19 Sep. 1979

(51) INT. CL.^{2} G01P 3/48

(52) Index at Acceptance
G1N 1A2C 1A2P 1A4 1D7 3S7 4A 4C 4D
4E 7E1 ACN

(19) THE PATENT OFFICE LONDON

(54) ROTATION SENSOR

(71) We, TELECO INC., a corporation organised and existing under the laws of the State of Delaware, United States of America, of 217 Smith Street, Middletown, Connecticut 06457, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed to be particularly described in and by the following statement:–

The present invention relates to rotation sensors and is particularly applicable to borehole drilling devices including sensing and telemetering means for periodically sensing borehole parameters and generating output signals which are transmitted to the surface only when the drill string has ceased rotation or reached a predetermined low rate of rotation.

In the field of borehole drilling, particularly oil and gas well drilling, the usefulness of a system capable of detecting certain parameters at the bottom of a drill string and transmitting such data to the surface during the course of drilling has long been recognized.

While some proposals and systems for borehole telemetry have involved arrangements where sensor packages are periodically lowered into and raised from a well hole, by far the most preferred arrangement is to have the parameter sensing apparatus permanently positioned at the bottom of the well, preferably in a lower segment of the drill string and to transmit the data to the surface. Several systems have been proposed for accomplishing such sensing and data transmission. One of the principal types of such systems is the mud pulse telemetry system wherein pulses are generated in the mud column in the drill string for transmission of data to the surface.

In the case of several classes of data, it is quite unnecessary to obtain readings more frequently than every 30 feet or so of depth of the well. This corresponds to readings every ¼ to 1½ hours at typical penetration rates of 120 feet per hour to 20 feet per hour. It therefore becomes desirable to turn off the downhole parameter sensing equipment during long periods of drilling to minimise wear which would otherwise result from continuous operation of the parameter sensors.

In order to determine the state of no rotation of the drill string, there is provided in accordance with the present invention a rotation sensor for sensing when the rate of rotation of a rotatable member in an ambient magnetic field falls below a predetermined minimum and for then activating a control mechanism, comprising a fluxgate magnetometer for generating an output signal as a function of the angular relationship of the magnetometer to the direction of the ambient magnetic field, said fluxgate magnetometer being mounted for rotation with said rotable member, means for generating and delivering an alternating input signal to said fluxgate magnetometer, said fluxgate magnetometer being arranged to produce when rotating a first output signal which is an even harmonic of said input signal, a first detector connected to receive said first output signal, means for generating a reference signal of the frequency of said first output signal, said reference signal being delivered to said first detector, said detector being arranged to compare the phases of said first output signal and said reference signal and to generate a second output signal representative of the phase difference, the frequency of which being representative of the rate of rotation of the rotable member, second detector means connected to receive said second output signal and arranged to generate a third output signal each time said second output signal crosses a reference level, and signal generating means connected to receive said third output signal

and arranged to generate a fourth output signal when said third output signal occurs at a rate representative of a rate of rotation below said predetermined minimum.

The invention also provides a method of sensing when the rate of rotation of a drill string in the earth's magnetic field falls below a predetermined minimum and for then activating parameter sensing means, comprising the steps of rotating fluxgate magnetometer means in the earth's magnetic field to generate an output signal as a function of the angular relationship of the magnetometer means to the direction of the earth's magnetic field, delivering an input signal to said fluxgate magnetometer means, said fluxgate magnetometer means having a first output signal which is an even harmonic of said input signal, generating a reference signal of the frequency of said first output signal, comparing the phases of said first output signal and said reference signal and generating a second output signal representative of the phase difference, the frequency of which is representative of the rate of rotation of the drill string, generating a third output signal each time said second output signal crosses a reference level, and generating a fourth output signal when said third output signal occurs at a rate representative of a rate of rotation below said predetermined minimum.

An embodiment of the invention will now be described by way of example with reference to the accompanying drawings, in which:

Figure 1 is a generalized schematic view of a borehole and drilling derrick showing an environment for the present invention.

Figure 2 is a view of a section of the drill string of Figure 1 showing, in schematic form, the drill string environment.

Figure 3 is a view, partly in section, of a detail of Figure 2.

Figure 4 is a view of the fluxgate magnetometer of the rotation sensor.

Figure 5 is a block diagram of the rotation sensor.

Figure 5A is a schematic showing of the digital filter of Figure 5.

Figures 6A, 6B and 6C are curves showing outputs at various stages of the rotation sensor of Figure 5.

Referring now to Figure 1, the general environment is shown in which the present invention is employed. It will, however, be understood that the generalized showing of Figure 1 is only for the purpose of showing a representative environment in which the present invention may be used, and there is no intention to limit applicability of the present invention to the specific configuration of Figure 1.

The drilling apparatus shown in Figure 1 has a derrick 10 which supports a drill string or drill stem 12 which terminates in a drill bit 14. As is well known in the art, the entire drill string may rotate, or the drill string may be maintained stationary and only the drill bit rotated. The drill string 12 is made up of a series of interconnected segments, with new segments being added as the depth of the well increases. The drill string is suspended from a movable block 16 of a winch 18, and the entire drill string is driven in rotation by a square kelly 20 which slidably passes through but is rotatably driven by the rotary table 22 at the foot of the derrick. A motor assembly 24 is connected to both operate winch 18 and rotatably drive rotary table 22.

The lower part of the drill string may contain one or more segments 26 of a larger diameter than other segments of the drill string. As is well known in the art, these larger segments may contain sensors and electronic circuitry for sensors, and power sources, such as mud driven turbines which drive generators, to supply the electrical energy for sensing elements. A typical example of a system in which a mud turbine, generator and sensor elements are included in a lower segment 26 is shown in U.S. Patent No. 3,693,428 to which reference is hereby made.

Drill cuttings produced by the operation of drill bit 14 are carried away by a large mud stream rising up through the free annular space 28 between the drill string and the wall 30 of the well. That mud is delivered via a pipe 32 to a filtering and decanting system, schematically shown as tank 34. The filtered mud is then sucked by a pump 36, provided with a pulsation absorber 38, and is delivered via line 40 under pressure to a revolving injector head 42 and thence to the interior of drill string 12 to be delivered to drill bit 14 and the mud turbine if a mud turbine is included in the system.

The mud column in drill string 12 also serves as the transmission medium for carrying signals of down the well drilling parameters to the surface. This signal transmission is accomplished by the well known technique of mud pulse generation whereby pressure pulses are generated in the mud column in drill string 12 representative of sensed parameters down the well. The drilling parameters are sensed in a sensor unit 44 (see also Figure 2) in a drill collar unit 26 near or adjacent to the drill bit.

Pressure pulses are established in the mud stream in drill string 12, and these pressure pulses are received by a pressure transducer 46 and then transmitted to a signal receiving unit 48 which may record, display and/or perform computations on the signals to provide information of various conditions down the well.

Referring briefly to Figure 2, a schematic

system is shown of a drill string segment 26 in which the mud pulses are generated. The mud flows through a variable flow orifice 50 and is delivered to drive a turbine 52. The turbine powers a generator 54 which delivers electrical power to the sensor in sensor unit 44. The output from sensor unit 44, which may be in the form of electrical or hydraulic or similar signals, operates a plunger 56 which varies the size of variable orifice 50, plunger 56 having a valve driver 57 which may be hydraulically or electrically operated. Variations in the size of orifice 50 create pressure pulses in the mud stream which are transmitted to and sensed at the surface to provide indications of various conditions sensed by sensor unit 44. Mud flow is indicated by the arrows.

For several classes of data or parameters to be sensed at the bottom of a well, it is quite unnecessary to sense the data and obtain readings more frequently than once every thirty feet or so of depth. This corresponds to readings every one quarter hour to one and one-half hour at typical drilling rates of one hundred twenty feet per hour to twenty feet per hour. It therefore becomes desirable to turn off the down hole sensing equipment during long periods of drilling, thereby minimizing wear of the sensors, transmitter and other parts of the telemetry system which would otherwise result from continuous operation. The apparatus shown in Figures 3 – 6 is directed to this feature of turning off the parameter sensing equipment by sensing and distinguishing between periods of rotation and absence of rotation of the drill string. The system requires a rotation sensor to detect drill string rotation and interrupt the delivery of electrical power to the well parameter sensors when the drill string is rotated, and, conversely, to permit the delivery of power to the well parameter sensors when the drill string is not rotated. A magnetic-detecting device which senses the earth's magnetic flux is used as a rotation sensor to detect the presence or absence of rotation of the drill string. This rotation sensor contains no moving parts, and, therefore, unlike other motion sensors which may contain moving elements, offers high reliability notwithstanding exposure to mechanical shocks and vibrations.

Referring now to Figures 2 and 3, some details of a drill string segment 26 are shown housing a rotation sensor 58 in accordance with this invention. Since both the rotation sensor and one or more other sensors in sensor unit 44 are magnetically sensitive, the particular drill string segment 26A which houses the rotating sensor and the other sensor elements must be non-magnetic section of the drill string, preferably of stainless steel or monel. The rotation sensor 58 may be incorporated in sensor unit 44 or may be separately packaged, and for the sake of convenience it is shown as part of sensor unit 44 in Figure 3. Sensor unit 44 is further encased within a non-magnetic pressure vessel 60 to protect and isolate the sensor unit from pressures down in the well.

Referring to Figure 4, the rotation sensor 58 is a ringcore fluxgate magnetometer which is used to determine the direction of the earth's magnetic field. Although theoretically many other kinds of flux detecting devices could be used, the ring-core fluxgate magnetometer is used because of its low power consumption and its rugged physical construction. Operation of the ring-core fluxgate magnetometer is based on the nonlinear or asymmetric characteristics of the magnetically saturable transformer which is used in the sensing element. As seen in Figure 4, the device has a toroidal or annular core 62 on which is appropriately wound (winding details not shown) an input or primary winding 64 and an output or secondary or sensing winding 66. Core 62 is made of a material with a square B-H hysteresis curve such as permalloy. The characteristic of this device is such that when the core is saturated by appropriate AC energizing of the primary winding in the absence of an external magnetic field, the output of the secondary windings, i.e. the voltage induced in the secondary windings is symmetrical, i.e. contains only odd harmonics of the fundamental of the driving current. However, in the presence of an external magnetic signal field such as the earth's magnetic field, the output voltage of the secondary windings becomes asymmetrical with second and other even harmonics of the primary frequency appearing at the output of the secondary windings. This asymmetry is related in direction and magnitude to the signal field and can be detected by several known techniques. Discussions of such fluxgate magnetometers can be found in the article by Gordon and Brown, IEEE Transactions on Magnetics, Vol. Mag-8, No. 1, March 1972, and the article by Geyger, Electronics, June 1, 1962 and in the article by R. Munoz, AA-3.3., 1966 National Telemetering Conference Proceedings, to all of which reference is made for a more detailed discussion of construction and theory of operation of the magnetometer.

As employed in the present apparatus, the input to the primary windings 64 drives core 62 to saturate twice for each cycle of the primary winding input. The moment in time that the core saturates is related to the ambient external magnetic field that biases the drive field in the core. That is, saturation of the core varies as a function of the intensity and direction of the earth's magnetic field, which field is indicated diagrammatically by the flux lines in Figure 4.

Sensor 58 is physically supported on a shaft 68 which is fixed in drill string segment 26A and is on or parallel to the axis of rotation of drill string segment 26A. While the drill string is being rotated, rotation sensor 58 is also being rotated in the ambient magnetic field of the earth. As rotation sensor 58 is rotated, the combined action of the input to primary windings 64 and the ambient magnetic field of the earth result in a varying phase shift in the second harmonic output at secondary windings 66.

Referring now to Figure 5, a block diagram of the rotation sensor output signal processing is illustrated. The input to primary winding 64 emanates from an oscillator 61, the output frequency of which is divided in half by divider 63 and then delivered to amplifier 65 and then delivered to primary winding 64. The output from secondary winding 66, which is tuned to the second harmonic of the primary winding input by capacitor 67, is delivered to a buffer amplifier 69 and then to phase detector 70A of detector 70. Detector 70 also includes low pass filter 70B and amplifier 70C. The output of oscillator 61 (which is equal in frequency to the second harmonic output of secondary winding 66) is also delivered to phase detector 70A. The phase angle of the second harmonic output of secondary windings 66 is a function of the rate of rotation of magnetometer 58, and that phase angle varies as a function of changes in the rate of rotation of magnetometer 58. The output of secondary winding 66 is compared with the output of oscillator 61 in phase detector 70A, where the difference in phase between the two is detected and delivered to low pass filter 70B. The output from filter 70B (when the drill string is rotating) is an alternating signal which varies in frequency as a function of the rate of change of the phase angle of the second harmonic output of secondary winding 66; i.e. the output of filter 70B varies in frequency as a function of changes in the rate of rotation of the drill string. The output from filter 70B is amplified in amplifier 70C and is then delivered to a zero crossing detector 72 which produces an output pulse each time the alternating signal from detector 70 crosses through the zero value. The pulses generated by crossing detector 72 (which are also a function of the rate of rotation of the drill string) are delivered to a digital filter 74 which produces output signals commensurate with states of rotation and no rotation.

Referring also to Figure 5A, digital filter 74 includes a counter-divider 75, an S-R type flip flip 76, J-K type flip-flops 77 and 78, and an AND gate 79 connected as shown. The output pulses from zero crossing detector 72 are delivered to the C input of counter-divider 75. Assuming the drill string is normally rotating, the pulses delivered to counter 75 cause counter 75 to overflow before being reset by a clock pulse CPN (which may be any selected subdivision of a clock pulse commensurate with a predetermined minimum rate of rotation), whereby the Q output of counter 75 goes high. The Q output of counter 75 is connected to the S input of flip-flop 76 and the high state of the Q output of counter 75 sets flip-flop 76, whereby the Q output of flip-flop 76 goes high and the $\bar{Q}$ output goes low. The $\bar{Q}$ output of flip-flop 76 is connected to the J input of flip-flop 77. Flip-flop 77 is initially cleared by a reset pulse ICLEAR which may be obtained from any convenient place in the system upon the initiation of power in the control system. The J input of flip-flop 77 is examined by the leading edge of each pulse CPN delivered to the C input of flip-flop 77 whereby the J input is delivered to the Q output. Thus, when the drill string is normally rotating, counter 75 repeatedly overflows and is then reset by clock pulses CPN; flip-flop 76 is repeatedly set by the Q output from counter 75 and reset by the upper level of clock pulses CPN; and the J input of flip-flop 77 is low each time it is examined by the leading edge of the CPN pulse at the C input of flip-flop 77. The Q output of flip-flop 77 is thus also low when the drill string is normally rotating; and a first output level indicating rotation is delivered from filter 74 (see Level X, Figure 6C).

Referring again to Figure 6, the various signals discussed above are shown graphically. The abscissa in each graph is time, and the ordinate in each graph is signal magnitude. Figure 6A shows the second harmonic output of detector 70, Figure 6B shows the pulse output of zero crossing detector 72, and Figure 6C shows the outputs from digital filter 74. From time T_1 to T_2 in all the graphs, the drill string is rotating at constant speed. As the drill string slows down when approaching a state of no rotation (after time T_2), the frequency of the alternating output of detector 70 decreases, thus resulting in a lower frequency output from zero crossing detector 72.

When the rotation of the drill string ceases, or the rate of rotation drops to a very low rate on the way to a state of no rotation, the pulses from zero crossing detector 72 drop below a predetermined minimum frequency corresponding to a predetermined low rate of rotation of the drill. Since the angular velocity of the drill string must go through decreasing levels in going from normal to zero rotation, a predetermined low rate (on the order of 3 rpm or less) can be used as a signal of no rotation, in that rotation is about to cease and will have ceased within the time required to in-

itiate operation of desired sensors which operate when rotation has ceased.

When rotation ceases or drops below the predetermined low rate, which signals the imminence of the state of no rotation, counter 75 does not overflow before being reset by the clock pulse CPN. Thus the Q output of counter 75 stays low, and flip-flop 76 does not get set. Since flip-flop 76 does not set, the $\bar{Q}$ output of flip-flop 76 is high and the J input of flip-flop 77 is high. The leading edge of clock pulse CPN then sets flip-flop 77 whereby the Q output of flip-flop 77 is high (see level Y of Figure 6C) indicating the state of no rotation. Thus, when the predetermined minimum frequency output from zero crossing detector 72 is maintained for a given time period from T_2 to T_3 (e.g. ten seconds), the digital filter output (i.e. the Q level of flip-flop 77) is switched, as shown in Figure 6C, to a second level indicating a state of no rotation (see level Y of Figure 6C). This second output level, commensurate with a condition of no rotation, is then used as a control signal for arming or powering the other sensor elements in sensor unit 44. prior to generation of this control signal, the other sensor elements in unit 44 are not powered. The control signal (i.e. the second output level from digital filter 74) is used as a signal to arm or deliver the power from generator 54 to valve driver 57 and to those other sensor elements, such as by operating flip-flops or arming gates to enable power to be delivered to the other sensor elements in sensor unit 44 or in any other desired fashion to that end.

WHAT WE CLAIM IS:–

1. A rotation sensor for sensing when the rate of rotation of a rotatable member in an ambient magnetic field falls below a predetermined minimum and for then activating a control mechanism, comprising a fluxgate magnetometer for generating an output signal as a function of the angular relationship of the magnetometer to the direction of the ambient magnetic field, said fluxgate magnetometer being mounted for rotation with said rotable member, means for generating and delivering an alternating input signal to said fluxgate magnetometer, said fluxgate magnetometer being arranged to produce when rotating a first output signal which is an even harmonic of said input signal, a first detector connected to receive said first output signal, means for generating a reference signal of the frequency of said first output signal, said reference signal being delivered to said first detector, said detector being arranged to compare the phases of said first output signal and said reference signal and to generate a second output signal representative of the phase difference, the frequency of which being representative of the rate of rotation of the rotable member, second detector means connected to receive said second output signal and arranged to generate a third output signal each time said second output signal crosses a reference level, and signal generating means connected to receive said third output signal and arranged to generate a fourth output signal when said third output signal occurs at a rate representative of a rate of rotation below said predetermined minimum.

2. A rotation sensor as claimed in claim 1 wherein said fluxgate magnetometer is a ring core fluxgate magnetometer.

3. A rotation sensor as claimed in claim 1 or 2 wherein the first output signal is the second harmonic of said input signal.

4. A rotation sensor as claimed in claim 3 wherein said reference signal is a signal having a frequency equal to twice the frequency of and in phase with the input signal to said magnetometer.

5. A rotation sensor as claimed in any preceding claim wherein said detector is a zero crossing detector arranged to generate a pulse signal on the zero crossings of the second output signal.

6. A rotation sensor as claimed in claim 5 wherein said signal generating means comprises a counter for counting the pulse of said third output signal, said counter being arranged to be reset at predetermined intervals, and logic means connected to receive the output from said counter to generate said fourth output signal in dependence on the state of said counter at said predetermined intervals.

7. A rotation sensor as claimed in any preceding claim arranged to sense the absence of rotation of a drill string in the earth's magnetic field.

8. A method of sensing when the rate of rotation of a drill string in the earth's magnetic field falls below a predetermined minimum and for then activating parameter sensing means, comprising the steps of rotating fluxgate magnetometer means in the earth's magnetic field to generate an output signal as a function of the angular relationship of the magnetometer means to the direction of the earth's magnetic field, delivering an input signal to said fluxgate magnetometer means, said fluxgate magnetometer means having a first output signal which is an even harmonic of said input signal, generating a reference signal of the frequency of said first output signal, comparing the phases of said first output signal and said reference signal and generating a second output signal representative of the phase difference, the frequency of which is representative of the rate of rotation of the drill string, generating a third output signal each time said second output signal crosses a reference level, and generating a fourth out-

put signal when said third output signal occurs at a rate representative of a rate of rotation below said predetermined minimum.

9. A rotation sensor substantially as hereinbefore described with reference to, and as illustrated in, the accompanying drawings.

10. A method of sensing the absence of rotation of a drill string substantially as hereinbefore described with reference to, and as illustrated in, the accompanying drawings.

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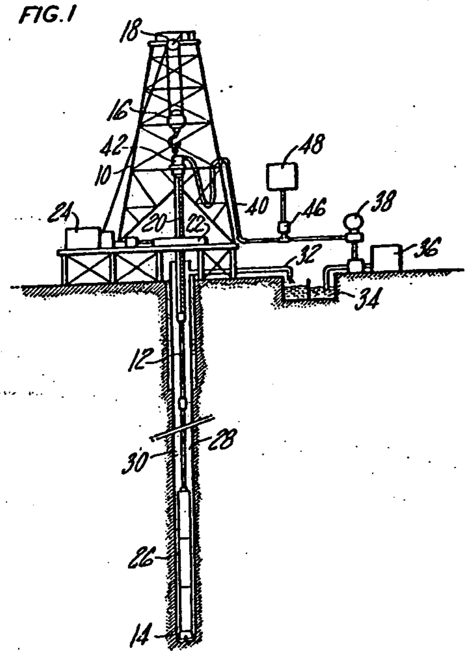
Printed for Her Majesty's Stationery Office, by Croydon Printing Company Limited, Croydon, Surrey, 1979.
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

1552864 COMPLETE SPECIFICATION

4 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

FIG. 1



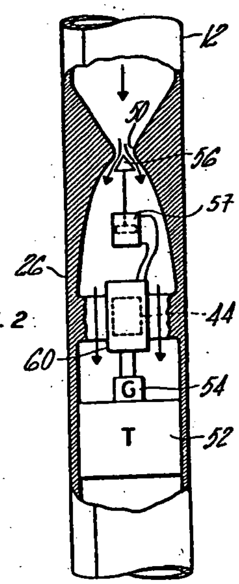
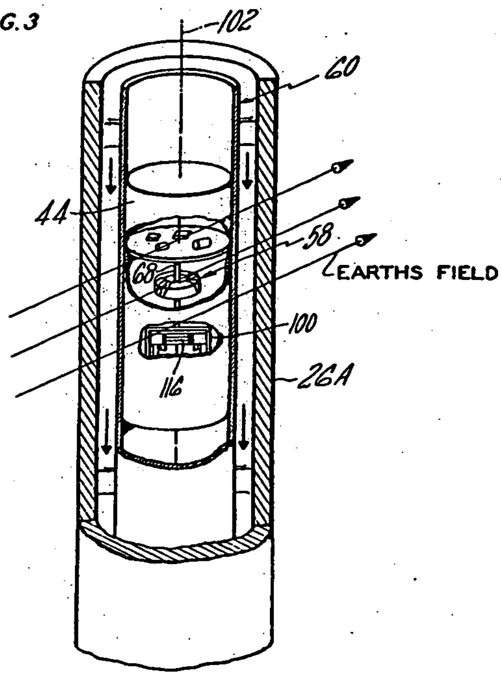


FIG. 2

FIG. 3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44
58
68
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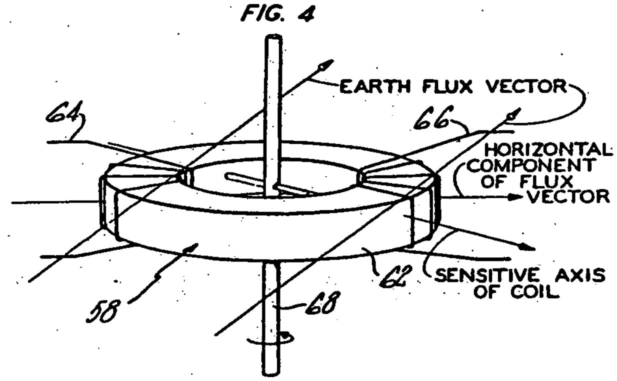
116
26A

FIG. 4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66
HORIZONTAL COMPONENT OF FLUX VECTOR
62
SENSITIVE AXIS OF COIL
58
68

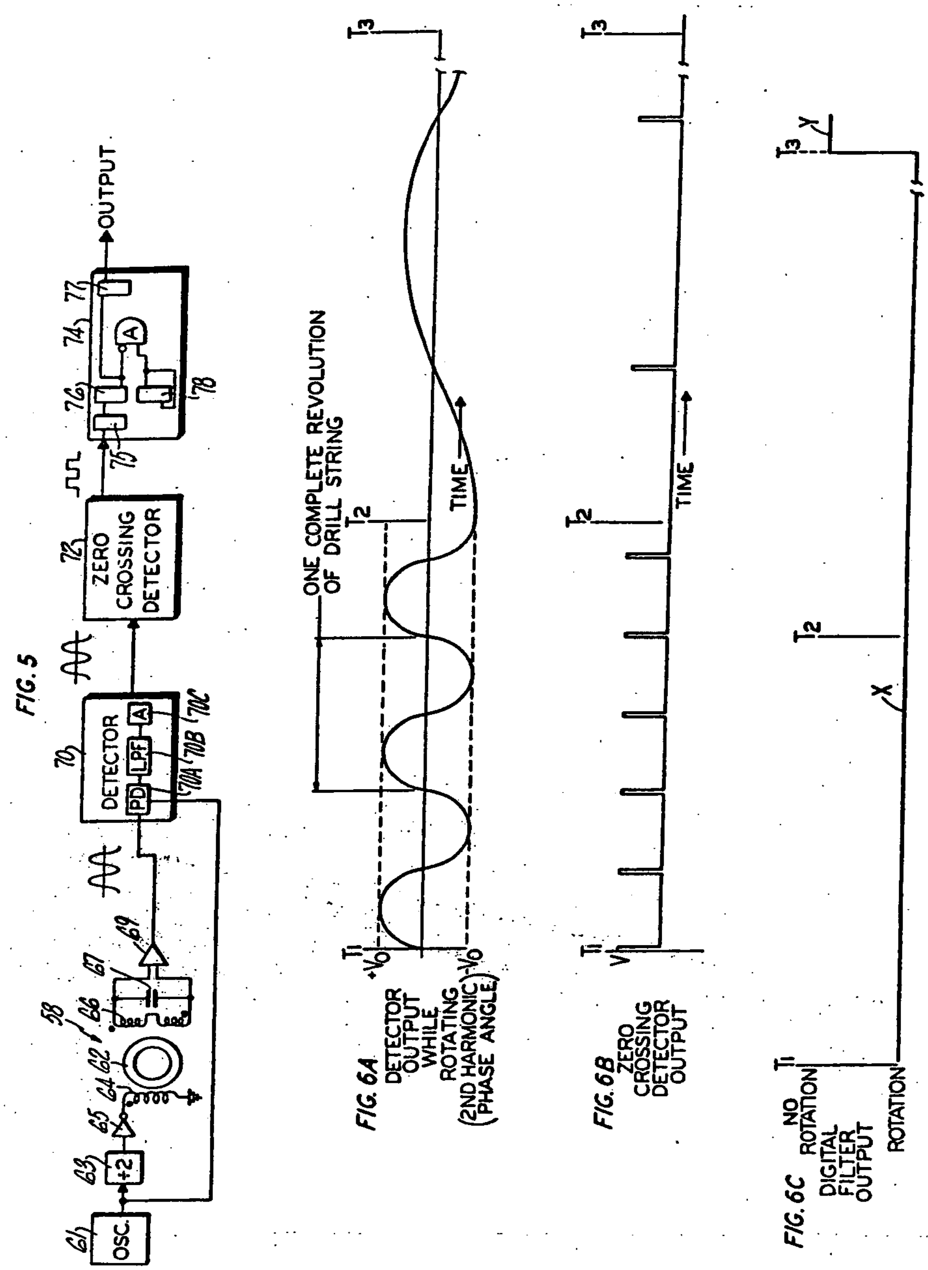


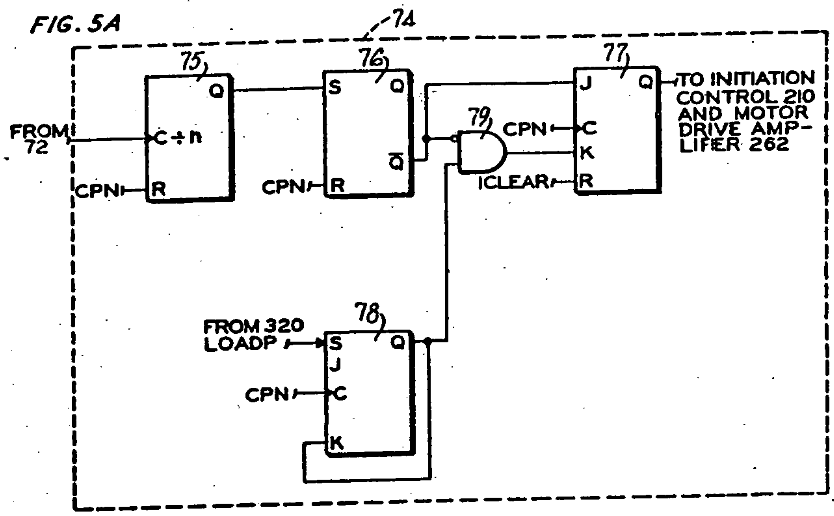
FIG. 5

FIG. 6A

FIG. 6B

FIG. 6C

FIG. 5A


74
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ICLEAR
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TO INITIATION CONTROL 210 AND MOTOR DRIVE AMP-LIFIER 262
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